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The Meteor Population

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RADIO METEOR PROJECT

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Introduction

The earth is continually bombarded with objects from outer space, and by studying the material as it arrives at the earth we can gain an understanding of the nature of the objects in the earth's environment. These objects cover a tremendous range of mass, from millions of tons to 10^{-16} gm, and their physical characteristics depend upon their masses. When the mass can be measured in kilograms, the object is invariably a solid piece of stone or iron, or stone and iron mixed. It is able to penetrate the atmosphere of the earth completely and land upon the surface. After retrieval, the object is known as a meteorite.

Between masses of approximately 10^{-12} gm and 10^{2} gm the particles are meteors that have been derived from the icy nucleus of a comet. Meteor particles invariably disintegrate in the upper atmosphere and never reach the surface of the earth intact. The population in the lower mass limit (10^{-12} gm) is composed of small particles that are decelerated without destruction in the upper atmosphere. These are known as micrometeorites and it is possible to collect them with high altitude rockets, or retrieve them as they float down to the surface of the earth.

The influx of objects into the earth's atmosphere is now fairly well established for the entire meteor population. The results of various measurements, given in Fig. 1, show that the number of particles falling into the earth's atmosphere increases with decreasing mass. It is also possible now to draw a monotonic curve over the entire range from micrometeorites to meteorites. The characteristics of the various groups in the meteor population are described

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Meteorites

The statistics pertaining to the fall of meteorites is based at present on an inhomogeneous set of data. More than 1,000 eye-witness accounts, mostly non-professional, are available of the fall of a meteorite that later was recovered and whose mass was determined. Several analyses in which the vagaries of the collection technique have been partially allowed for (Nininger 1933, Öpik 1958, Hawkins 1959, 1960, 1963a, and Brown 1960) have been made to determine the rate of arrival of meteorites. A photographic network is now being constructed in the Prairie regions of the United States to obtain more reliable statistics (McCrosky 1963), but until fresh data are available we must rely upon the meteorite catalogues.

Meteorites are classified as stones or irons. The stones contain minerals such as olivine, pyroxene, plagioclase and troilite, and have an average density of 3.4 gm cm^{-3}. Most stones contain chondrules, small spherules about 1 mm in diameter; they are usually a mixture of orthopyroxene and olivine.

The irons are largely metallic, being coarse crystals of an iron-nickel alloy. The percentage of nickel varies from about 3 to 15, and the average density is 7.8 gm cm^{-3}.

The crushing strength for stone meteorites varies from 3.8×10^6 gm cm^{-2} to 6.3×10^4 gm cm^{-2}, although one or two meteorites have crumbled at values somewhat lower than this. The average crushing strength for stone is approximately 3×10^6 gm cm^{-2}. The crushing strength for an iron is considerably higher, although occasionally an iron will break up under moderate stress because of weaknesses in the boundary between adjoining crystals.

It has been shown (Hawkins 1963a) that the stone and the iron meteorites differ in their mass distributions. The number N of stones that fall on one square kilometer of the earth's surface during the period of a year, with mass greater than or equal to m, is given by the relation

$$\log_{10} N = -0.73 - \log_{10} m \qquad (1)$$

Note that N is a cumulative number that is of direct interest in the problem of space hazards since it gives the total number of impacts of objects above a certain limiting size. Equation (1) gives the influx as a function of the mass "in space" of the meteorite; this mass will be considerably reduced by ablation processes in the atmosphere. The number of irons that impact is given by the relation

$$\log_{10} N = -3.51 - 0.7 \log_{10} m \tag{2}$$

It can be seen from these equations that the cumulative number of stony meteorites varies as m^{-1}, whereas the number of irons varies as $m^{-0.7}$. This represents a difference in the mass distribution of the objects, which is important for several reasons. Firstly, although the average-sized meteorites are usually stones, extremely large meteorites are usually irons. At a mass of 100 kgm the stones outnumber the irons in the ratio 20:1. At a mass of 10^{10} kgm the irons outnumber the stones by 10:1. Stones and irons occur in equal numbers at a mass of about 10^{6} kgms, which forms a convenient point at which to divide the two regimes of meteorites. Secondly, the mass distribution yields information concerning the origin of the meteorites. Equation (1) is the same as the comminution law obtained when terrestrial rocks are subjected to grinding and crushing for a considerable length of time. Equation (2) represents a moderate degree of crushing. This is consistent with the hypothesis that meteorites are asteroidal fragments formed by collision processes in space and that the stone fragments have been crushed to a greater degree than the irons, owing to their low crushing strength (Hawkins 1960). Thirdly, Equation (2) is consistent with the number of asteroids that cross the orbit of the earth, and we may conclude that objects such as Eros, Apollo and Amor are probably composed of iron.

<u>Cometary Meteors</u>

Although a few stone and iron fragments with masses less than 100 gm are undoubtedly present in the meteor population, the bulk of the material in this range is the solid debris ejected from the icy nucleus of a comet. At least 50 per cent of cometary meteors are sporadic; the orbital elements form a smooth distribution and there are no discernible sub-sets. It is therefore necessary to describe sporadic meteor orbits on a statistical basis. The flux of sporadic meteors, N km^{-2} $year^{-1}$, is given as a function of the mass, m gm, by the relation:

$$\log_{10} N = +0.41 - 1.34 \log_{10} m \qquad (3)$$

The result has been obtained from a photographic survey (Hawkins and Upton 1958). In the original determination the mass of a meteor of a given brightness was not known with certainty and equation (3) is based upon a revised scale in which the mass of a meteor with zero visual magnitude and a velocity of 30 km sec^{-1} is 4.4 gm. There are still uncertainties in the mass scale (Whipple 1963, Lazarus and Hawkins 1963), but equation (3) is probably trustworthy to within a factor of 5. There are diurnal and seasonal variations in the meteor flux which are of the same order of magnitude as the uncertainty in equation (3).

Approximately 50 per cent of the meteor flux comes from the major and minor streams, and must be added to the sporadic flux. Several of the major streams, such as the Perseids and Taurids, are related to known comets. Other streams are not associated with a known comet, and presumably the parent comet has disintegrated. The most important of these streams are listed in Table 1. The flux from streams is limited to a few days of maximum activity on certain calendar dates, and during these periods an extra component, N_s, is added to the flux. If we define the stream activity in terms of the sporadic rate such that $N_s = kN$, then the factor K is that given in Table.1.

TABLE 1

Stream Flux

Stream	Dates	k
Quadrantids	Jan 2-3	5.0
Lyrids	Apr 20-21	0.5
Daytime Arietids	June 5-11	5.0
Daytime Perseids	June 5-11	4.0
Aquarids	July 22 - Aug 7	2.0
Perseids	Aug 9-14	5.0
Orionids	Oct 20-24	2.0
Taurids	Oct 10 - Nov 25	0.5
Geminids	Dec 10-16	5.5

Stream meteors, of course, move in almost parallel paths and the flux given in Table 1 is for an area continually oriented in a direction perpendicular to the stream.

Photographic observations have shown that cometary meteors are extremely fragile. Meteors with an initial mass of approximately 100 gm shed fragments continually during the luminous trajectory in the upper atmosphere (Jacchia 1955). At smaller sizes, at a mass of approximately 0.1 gm (visual magnitude +3), the meteor occasionally disintegrates at the beginning of the luminous trail (McCrosky 1955). From the height at which disintegration takes place and from the velocity of the meteor, it is possible to calculate the dynamic pressure exerted on the body. One meteor in three, in this range, breaks up when the pressure exceeds 10 gm cm^{-2}. This is an extremely low crushing strength by terrestrial standards, comparable to that of cigar ash.

Whipple (1963) has discussed the photographic observations made on meteors with masses between the approximate limits of 1 gm and 100 gm, and with an average density close to 0.4 gm cm^{-3}. From this low density and the low crushing strength it has been inferred that cometary meteors are loose aggregates of small particles forming an open or porous structure. The solid particles are presumed to be composed of minerals similar to those found in stony meteorites, although no direct chemical analyses have been made so far because the meteor material is too fragile to reach the surface of the earth in any large quantities. Spectrograms of brighter meteors show the presence of iron, calcium, sodium, silicon and other relatively abundant elements. It has not yet been possible to obtain spectrograms of meteors fainter than a magnitude ~ 0, corresponding to a mass of 5 gm.

Equations (2) and (3) and Figure 1 show that the flux of cometary meteors equals the flux of meteorites at a mass of approximately 300 gm. The regime of cometary meteors has been defined by extending equation (3) from a mass of 300 gm to a mass of 10^{-13} gm. At first sight this extrapolation might seem unwarranted since the photographic observations do not extend below a mass of 10^{-2} gm. However, since there is confirmation from radar data at a mass of 10^{-4} gm, and since the extrapolation agrees with the number of particles collected by high altitude rockets at a mass of 10^{-13} gm, this extrapolation is probably valid to perhaps an order of magnitude.

Using a six-station radar system (Hawkins 1963b), Hawkins and Southworth (1963) have studied the influx rate and physical characteristics of meteors close to the middle of the range of cometary meteors. Preliminary measurements of the flux of meteors with mass greater than 4×10^{-4} gm yields the value shown in Figure 1. The determined value is an order of magnitude greater than the value expected from Equations (3) and further work is required to investigate this discrepancy. However, considering the degree of the extrapolation, the point may be taken as a preliminary confirmation of Figure 1.

The small particles investigated by the radio technique clearly show the effects of fragmentation. At the limit of velocity measurements, 10^{-3} gm, most of the meteors are observed as a closely packed cloud of many independent fragments. The meteor has totally disintegrated at or before the onset of ionization. Because of this effect, the density of the meteor before breakup cannot be measured. However, it is presumed that the density in space is comparable to the value of 0.4 gm cm^{-3} as found for the larger objects observed in the photographic program.

Definite changes appear in the orbits of sporadic meteors as one proceeds from a mass of 1 gm to a mass of 10^{-3} gm. As one proceeds to smaller masses the orbits show smaller semi-major axes and smaller eccentricities. This effect is apparent from a detailed study of the orbital distributions as a function of mass. The effect can also be shown statistically by comparing the average observed velocities of sporadic meteors as a function of mass. Figure 1a shows the average velocity over a range of visual magnitudes from +6 to +9. There is a general decrease in velocity amounting to approximately 5 km sec^{-1} over an interval of 3 magnitudes (Hawkins, Lindblad and Southworth, 1963a). A similar result has been obtained for meteors with radiants near the Apex by Eshleman and Gallagher (1962), who found that between magnitudes of +7 and +12 the average sporadic velocity decreased by 2 km sec^{-1}. This value is probably an underestimate because Eshleman and Gallagher did not determine any values of velocity below 35 km sec^{-1}.

These authors have suggested that at a mass of approximately 10^{-4} gm "The so-called sporadic background appears instead to consist of particles concentrated into a very large number of shower orbits. Characteristic dimensions of these particle concentrations must be very small, by astronomical standards, since the intersection of a group with the earth may take on the order of one day or less. It is suggested that the earth may be immersed in about ten particle groups at one time. It appears that there may be millions of such groups in the solar system ..." These conclusions were based upon an interpretation of the fluctuations in hourly rate reported by a sensitive radar system. They are not borne out by a detailed study of the orbits of meteors in this size range. A comparison program has been carried out on 2300 meteor orbits with masses between 10^{-1} and 10^{-3} gm. (Hawkins, Lindblad, and Southworth 1963b). Most of the streams found were the well known major and minor streams previously discovered visually and photographically. There is no detailed structure within the sporadic orbits, and it is therefore possible to describe them only in terms of broad statistics.

Approximately 30 per cent of sporadic meteors at a mass of 10^{-2} gm are moving in orbits of low eccentricity and high inclination (Davies and Gill 1960; Hawkins 1962). This is quite different from the alignment in the plane of the solar system found in photographic measurements. This second grouping has been provisionally called the "toroidal group," which was probably formed by the long-term perturbations from the planet Jupiter.

Micrometeorites

The deceleration of a meteor in the atmosphere depends on the ratio of cross-sectional area to mass. Thus, the deceleration is inversely proportional to diameter, and small objects undergo a severe deceleration. Whipple (1950) and Öpik (1937) have pointed out that a small object can be decelerated without melting, and arrive at the surface of the earth intact. These objects are aptly termed micrometeorites, and their recovery at ground level and in the upper atmosphere is of great interest.

Whipple (1950) assumed that the energy generated by passage through the upper atmosphere is quickly conducted to the interior of the micrometeorite. The object then reradiates this energy as a gray-body in isothermal surroundings, and will remain solid provided that the surface temperature does not rise above the melting point of the material. The critical size of a solid micrometeorite is given in Table 2 as a function of velocity and density of the object. If the meteor melts, it will still escape destruction if the temperature remains below that of vaporization. Under these conditions the maximum diameter will be somewhat greater than those given in Table 2. A micrometeorite of the size given in Table 2 reaches a maximum temperature at a height which is approximately 10 km above the beginning height of cometary meteors. The particle decelerates rapidly after attaining maximum temperature and soon reaches a terminal velocity. Micrometeorites smaller than those listed in Table 2 are decelerated more rapidly, and reach a maximum temperature at higher heights than those given in Table 2.

Several methods have been used to collect micrometeorites. Sticky plates have been exposed at ground level in dust-free regions. Microphones have been carried on high altitude rockets and satellites to detect the impact of small objects. The most direct method, and the one that is perhaps less subject to contamination and misinterpretation, is the rocket-borne collection and recovery technique of Hemenway and Soberman (1962). A collector rocket was fired from White Sands, New Mexico, on 6 June 1961, reaching an altitude of 168 km. Several space layers of Mylar foil were exposed to determine the rate at which the foil was punctured. Several types of collecting surfaces were also exposed to trap the micrometeorites upon impact. Extreme care was taken to avoid the possibility of terrestrial contamination. Before launching, all collecting surfaces were coated with a thin film of nitrocellulose film. The collecting surfaces were shadowed by an atomic beam, both before launching and after recovery, so that extraterrestrial particles could be readily identified.

TABLE 2

Micrometeorite diameters

Velocity ($km\ sec^{-1}$)	Height of maximum temperature (km)	Maximum diameter, (Microns) Density = 3	Density = 0.3 $gm\ cm^{-3}$
15	92	38	380
20	96	18	180
25	100	10	100
30	103	6	60
40	108	3	30
50	113	1.4	14
60	117	0.9	9
70	120	0.6	6

Millions of particles were collected during approximately 200 seconds of exposure but, of course, only a sample of these particles could be investigated. In general the particles could be divided into three types as illustrated in Figures 2, 3, and 4. Figure 2 shows what was termed a "fluffy" particle, very irregular in shape and open in structure. During its interaction with the atmosphere, a particle of this type would necessary exhibit a low effective density. A loose aggregate of this type is remarkably close to the physical characteristics derived for cometary meteors from photographic studies. Figure 3 shows a more compact object that, like the particle in Figure 2, has not melted during deceleration. Figure 4 shows a small spherule and the crater that it formed in the aluminum coating on nitrocellulose film.

Note that the typical particles shown in Figures 2, 3, and 4 are well within the size range of micrometeorites as given in Table 2. The particles must have arrived at the collecting films at very low velocity. For example, the sphere in Figure 4 did not carry sufficient energy to puncture the thin nitrocellulose film that backed the aluminum layer. This indicates that the particles were falling with terminal velocity in the atmosphere and is further confirmation that the particles are micrometeorites.

Hemenway and Soberman give the observed flux of particles on the collecting surfaces of the rocket as a function of the size of particle. To obtain the true influx of micrometeorites it is necessary to apply a correction for the velocity of the rocket. It is assumed that all particles were falling through the atmosphere with terminal velocity and that the flow of particles in each size range had reached a condition of steady state. Under these conditions the observed flux would be the true flux if the rocket were stationary. A correction factor was then applied to allow for the vertical motion of the rocket. Assuming a mean density of 3.0 gm cm^{-3} we may represent the flux by the expression

$$\log_{10} N = 12.43 - 0.39 \log_{10} M . \tag{4}$$

The cumulative flux, N, is the number of particles km^{-2} $year^{-1}$ with mass greater than or equal to m gm.

Equation (4) was found to hold for particles with diameters up to 2.5 microns, corresponding to a mass of approximately 10^{-13} gm. At this diameter a pronounced change appeared in the gradient in the mass distribution, and the value agreed with that of equation (3) within the limits of experimental error. Thus it is reasonable to presume that the regime of cometary meteors extends to masses as small as 10^{-13} gm. As further corroboration, note that the absolute value of flux at 10^{-13} gm is in agreement with the absolute value determined by extrapolating the photographic data. It is also in fair agreement with the flux determined by microphone impacts (Dubin and McCracken 1962). Hemenway and Soberman (1962) attribute the change of slope in the mass distribution to the effects of radiation pressure acting on the particles in interplanetary space.

The extraterrestrial particles were examined with an electron microscope, which yielded the photographs in Figures 2, 3, and 4. Individual particles were examined by an electron diffraction technique to test for crystal structure. An electron probe was used to excite X-ray fluorescence to determine the chemical constituents. One or two particles were subject to neutron activation to search for specific elements.

The majority of the particles showed no detectable crystal patterns. The reason for this has not been established, although various possibilities suggest themselves. The small particles formed in interplanetary space may be completely amorphous; the particles may be composed of a multitude of minerals in micro-crystalline form; the particles, although originally crystalline, may be heated sufficiently to destroy the crystal structure during passage through the atmosphere. Of these suggestions, perhaps the second is the most likely. The fluffy fragments show evidence of being composed of microscopic particles with individual masses of about 10^{-15} gm. If these particles represented a hundred or more different minerals, then no crystal pattern would be detected.

Approximately one micrometeorite in a hundred does show a definite diffraction pattern. These exceptional particles contain a predominant mineral. Although several crystal spacings have been determined, the nature of the mineral has not been identified.

Most of the micrometeorites examined do show a crystal pattern when the particle has been vaporized in the electron beam and recondensed on the adjoining film. The most predominant diffraction pattern observed corresponds to three possible crystal structures - austenite, taenite, and copper. It has not been possible to decide which of these possibilities is correct, although it should be noted that taenite is a well-known constituent of the larger meteorites.

The electron probe and neutron activation show the presence of the following chemicals: Al, Si, Fe, Ni, Ti, Ca, Mg, and Cu. The abundances varied from particle to particle although aluminum, silicon, and iron were frequent constituents. There was a possibility that the aluminum and copper had been introduced as contaminants.

Space Hazards

The flux shown in Figure 1 represents a revision of the estimates given by Whipple (1963), and covers a greater variation of mass. The physical characteristics of the projectile are given as a function of mass, and the population may be conveniently divided into the four regimes - irons, stones, cometary meteors, and micrometeorites. The results, and our current knowledge of penetration and cratering, can be used to estimate the damage sustained by a space craft. For example, Herrmann and Jones (1962) have shown that the depth p of a crater, formed in a semi-infinite target by a projectile of mass m, is given by the semi-empirical relation

$$p = 1.70\, m^{1/3}\, \rho^{1/3}\, \rho_t^{-2/3}\, \log_{10}(1 + 0.25\, \rho^{2/3}\, \rho_t^{1/3}\, v^2 H^{-1}) \qquad (5)$$

where ρ is the density of the projectile, ρ_t is the density of the target, v is the impact velocity and H is the Brunell hardness.

Equation (5) is given in cgs units. A thin plate of thickness P will be punctured if (Whipple 1963)

$$P \leq 1.5\ p\ . \tag{6}$$

At the large end of the mass scale of the meteor population the problem is to calculate the probability that a surface will be punctured during flight. At the small end of the mass scale the problem is to compute the rate of erosion of the surface caused by many successive impacts.

As an example, the probability of collision for Project Apollo is also given in Figure 1. The probabilities are based on an estimated cross-section of 10 m^2, and an exposure time of 10 days. The probability of collision with a stone or iron meteorite is trivially small, although, of course, the effects of impact would not be so trivial if they did occur. No space craft could be designed to withstand the catastrophic effects of collision with a meteorite. At a mass of 10^{-5} gm the probability of collision is 1.0. According to the impact theory this is sufficient to penetrate an aluminum skin of thickness 0.05 cm if the meteor density is 0.4 and the velocity is 22 km per sec^{-1}. At a mass of 10^{-12} gm, the Apollo vehicle will suffer 10^{10} collisions. This will produce approximately 1000 erosion pits per mm^{-2}.

In using equations (3) and (4) to estimate space damage several factors have to be borne in mind. It has been suggested that the space density of micrometeorites decreases as one proceeds away from the vicinity of the earth (Whipple 1961), although there is still some uncertainty in the result (Dubin and McCracken 1962). If a dust cloud does exist in the vicinity of the earth, then the flux given in Equation (4) may be considerably reduced in deep space. The micrometeorites detected by rocket were assumed to be falling with terminal velocity. Thus, a satellite moving through the layer of micrometeorites will tend to sweep up particles at a rate greater than that given in Equation (4).

The flux will be increased approximately by the ratio of the velocity of the space craft to the terminal velocity of the micrometeorites. For both micrometeorites and cometary meteors a certain amount of shielding is produced by the earth itself. The value of N in Equations (3) and (4) is reduced, although never by more than a factor of 2 for a randomly oriented space craft.

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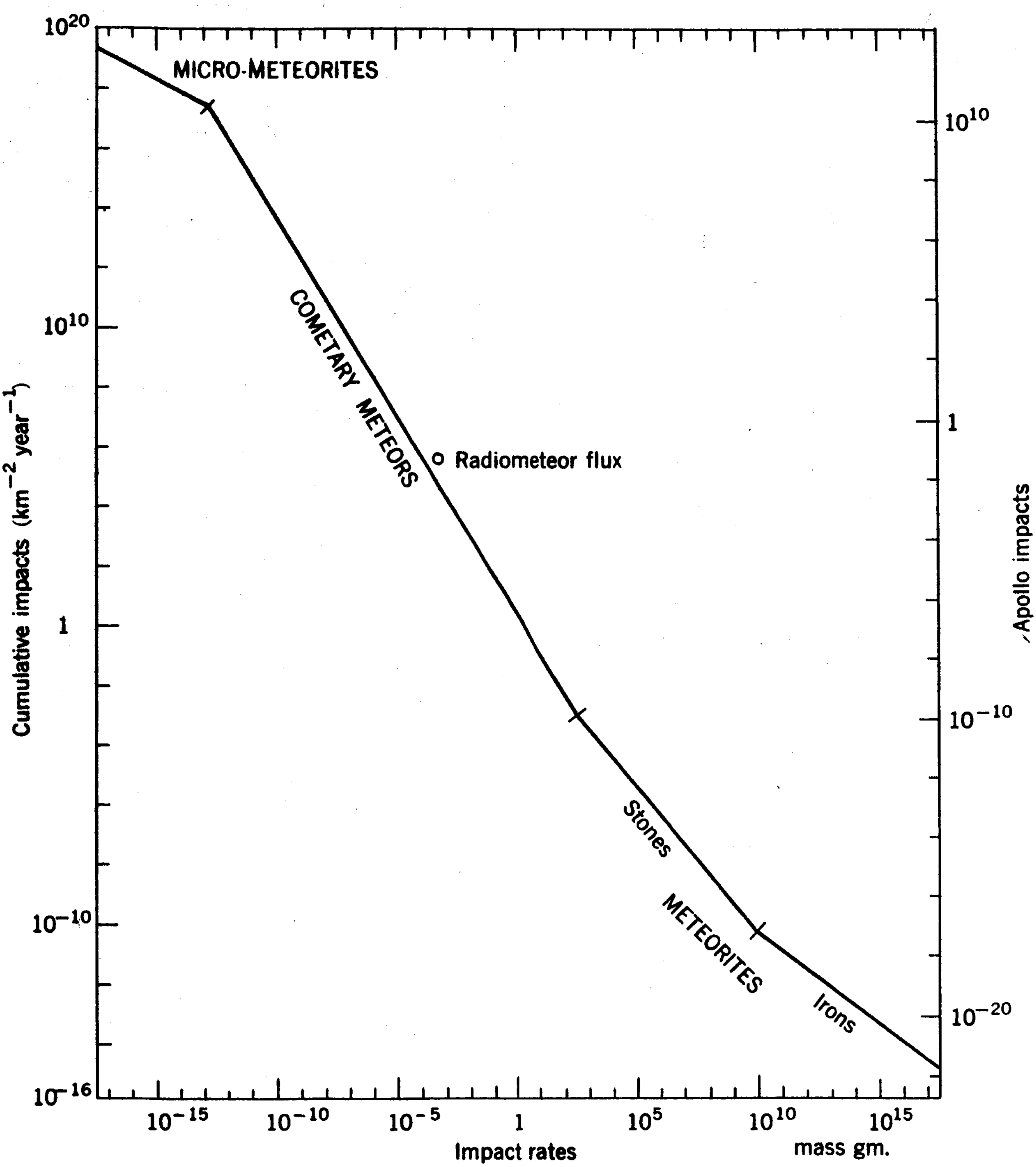

FIGURE 1

Flux of Extraterrestrial Objects

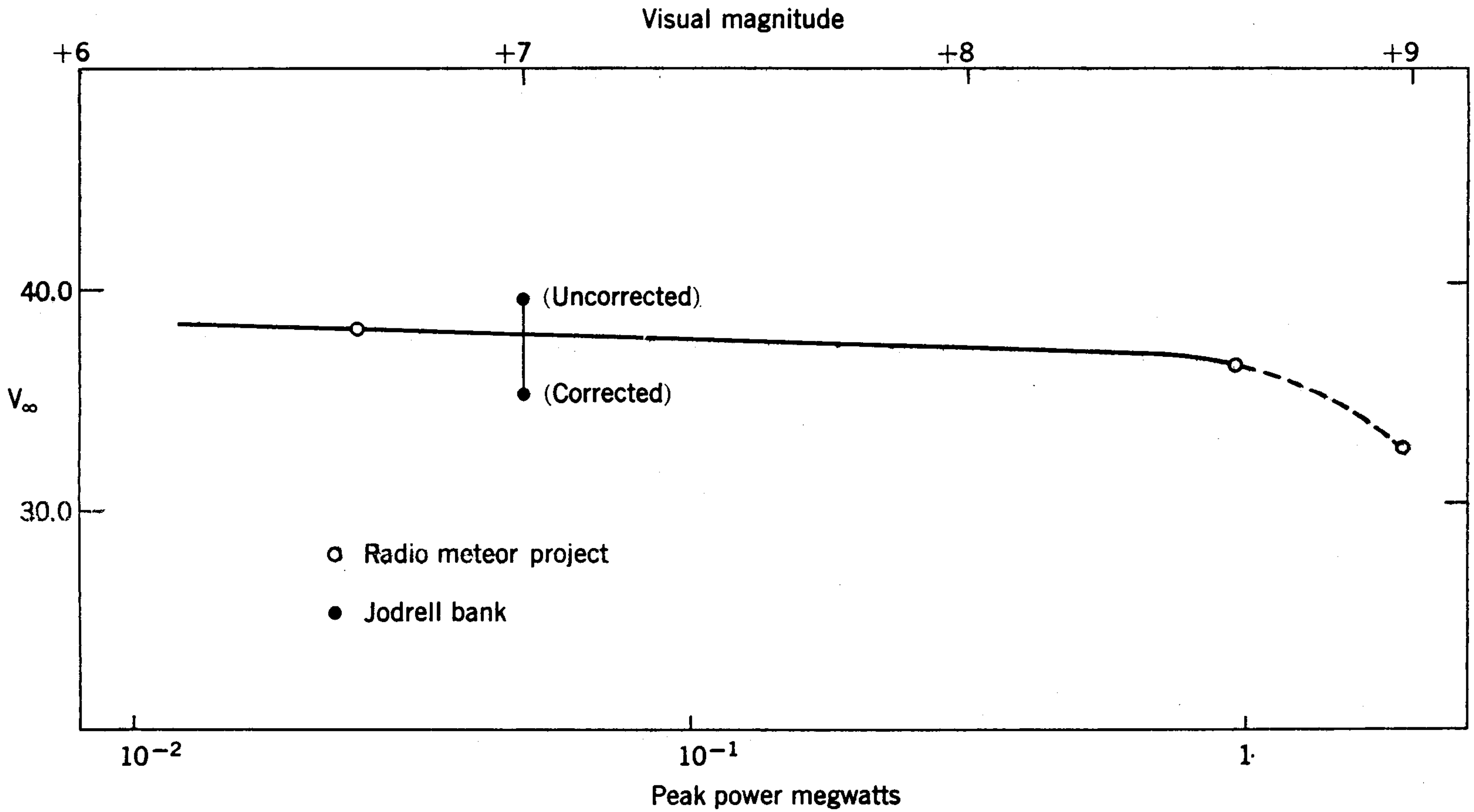
Visual magnitude
+6
+7
+8
+9
40.0
V_∞
30.0
(Uncorrected)
(Corrected)
Radio meteor project
Jodrell bank
10^{-2}
10^{-1}
1
Peak power megwatts

FIGURE 1a

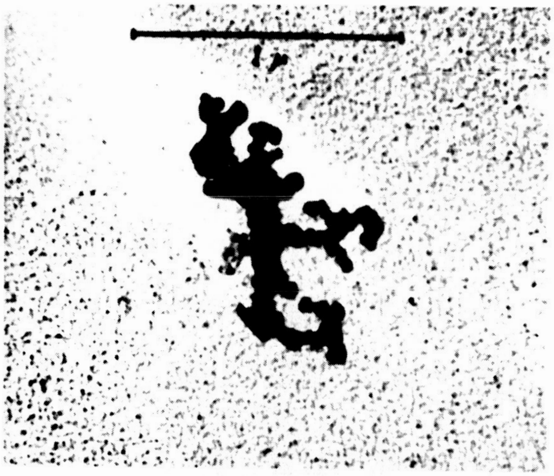

Figure 2

A Fluffy Micrometeorite

Figure 3

A Compact Micrometeorite

Figure 4

A Micrometeorite Spherule